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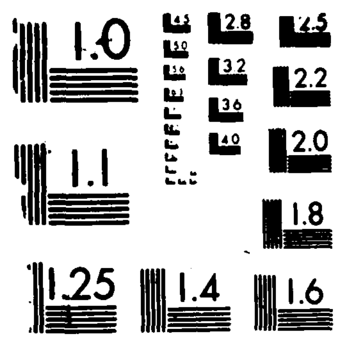

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A PRELIMINARY STUDY ON THE EFFECTS OF THE JOINTS AND CRACKS ON THE DYNAMIC PROPERTIES OF THE ROCK MASS AND ITS STRUCTURE

by

Wang Qizheng

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HUMAN TRANSLATION

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A Preliminary Study on the Effects of the Joints and Cracks on the Dyhamic Properties of the Rock Mass and its Structure

by Wang Qizheng

Tsinghua University

In this paper, the dynamic analyses of two groups of column rock structure including eight different crack cases are carried out by the finite element method. The effects of cracks on the structure's dynamic behavior were studied, and an estimation method of the effective dynamic elastic modulus of the cracked rock material was obtained. The results show that the dynamic response for a simple structure with cracks can be estimated using a dynamic analysis of the structure without cracks which has orthogonal anisotropic properties. Finally, a hill model was used to study the effect of cracks on the damping and to prove the above conclusions as well.

1. Preface

During the anti-seismic or dynamic calculation for a hydraulic structure or other kinds of structure, the rock's dynamic stability often needs to be considered. However, the rock itself normally has many joints, cracks or fractures. They will directly affect the mechanic behaviors of a rock and the dynamic properties of a hill. Meanwhile, the fact of earthquake damage has shown that a concrete dam can crack under strong vibrations. The cracks not only reduce the strength of the dam, but also affect the dynamic properties of the rock itself. Therefore, studies on the effects of the joints and cracks on the dynamic properties of rock and concrete as well as other structures are extremely necessary.

It no longer is a linear problem for the dynamic properties of the cracked material and its structure. Strictly speaking, its motion characteristics can no longer be described by vibrational modes. It is even more complicated for the crack propagation problem of a structure under a moving load. Currently, the study of this subject has not seen widely both at home and abroad. Under the conditions of a small moving load and small deflection, however, the rock material, which has joints and cracks, as well as its structure can be treated approximately as an elastic body cut by cracks.

II. Calculation Model and Methodology

In order to simplify the problem, a study is conducted by taking a column rock structure as shown in Fig. 1 and treating it as a plane stress problem. A total of eight different cracking cases, sorted into two groups, horizontal and vertical, respectively, are given to the model. Under general conditions, the horizontal cracks can be considered as being closed completely by its own weight. When the moving load is small, within the material elastic range, the problem is the same as the case without cracks. Therefore, the group A models which have vertical cracks as shown in Fig. 1 including PV-2, PV-3 as well as PV-9 represent the cases of an incomplete penetrated crack and a high crack penetrating rate but still having some portions (such as a and b) where the crack is either being squeezed by the rock itself or not yet completely penetrated. The PV-5 is used to model the case of a layer rock which contains a different number of vertical cracks. The horizontal cracks of group B are mainly used to study the effects of cracks on the material elastic modulus.

The finite element method is adopted to conduct the dynamic analyses of a structure, and the elements are the rectangular isoparametric elements. The structure is divided into meshes as shown in the PV-2 model of Fig. 1. Assume the crack is a gapped crack, the mass points at both sides of the crack (such as 8 and 9) belong to different elements and they are independent upon each other during vibration, except the two end points of the crack

(such as 3 and 14). The boundary condition is that all boundary nodes are free except the base points 1 through 5 which are fixed.

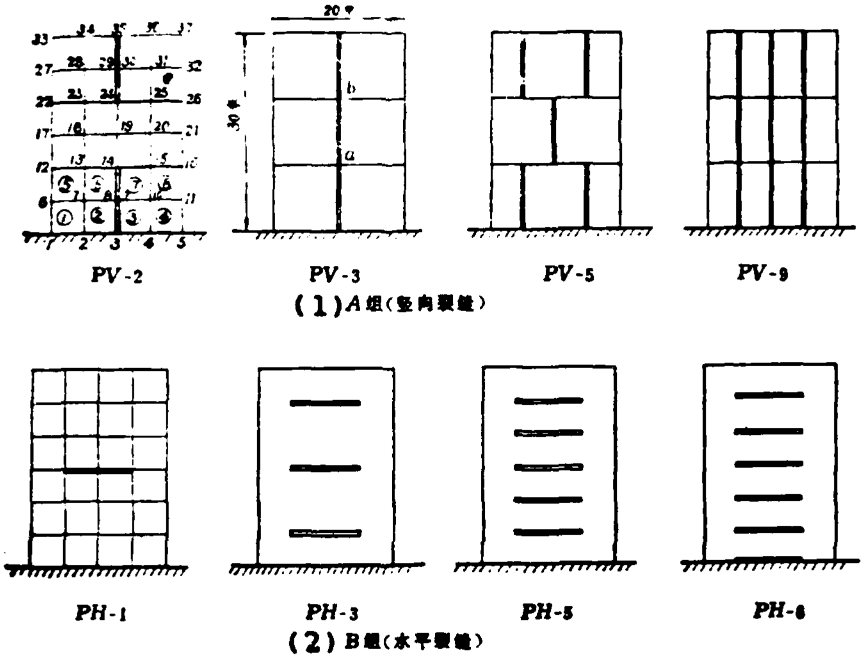

Fig. 1 Two groups totaling eight case of cracks are calculated by the finite element method.
Key: (1) Group A (Vertical cracks);
(2) Group B (Horizontal cracks).

When calculating the natural vibration property of a structure, the non-damping free vibration equation of a structure is applied.

$$M\ddot{X}+KX=0. \tag{1}$$

The characteristic equation can be solved by applying the determinate searching method. Only the first 5 to 7 vibration

modes are selected.

During the calculation, the properties of the material used in the calculation are the elastic modulus $E_o = 2\times10^6$ tone/m^2, the Poisson's ratio $\mu_o = 0.25$, and the weight density $\gamma = 2.6$ ton/m^3.

III. Effects of the Cracks on the Free Vibration Properties of a Column Structure.

Table 1 lists the natural frequencies of the structure with different vertical cracks. Fig. 2 shows the comparison of different vibration patterns of model PV-9 and the corresponding pattern of the case without cracks. Since all of the vibration patterns are symmetric with respect to the axial axis, only the left side vibration patterns were plotted for the case without cracks. From Table 1 and Fig. 2, we see:

(1) The frequency of each mode decreases when the crack number increases,

(2) The effect of cracks on the free vibration pattern depends upon the vibration mode. Generally speaking, the effect of cracks on the high mode is more serious than that on the low mode, especially, for the high, normal symmetry vibration case.

All the above facts show that the effects of cracks on the free vibration properties depend not only on the number of cracks, but also on the crack orientation, or more precisely said on the relationship between the displacement direction of each point mass and the crack orientation during the vibration process. For the

high, normal symmetry vibration pattern, the displacement of its point mass mostly is orthogonal to the crack orientation; therefore, the effects of cracks on the vibration pattern are remarkable. As for those particular vibration patterns, the structure with cracks is no longer the same as that without.

Table 1 The natural frequencies of a column rock structure with different case of cracking (Hz).

(1)裂缝情况	(2) 计算模型编号	(3)反对称振型				(4)正对称振型		
		1	2	3	4	1	2	3
(5)无缝	P-0	7.73	25.14	49.55	57.32	22.91	51.70	66.17
(6)竖向裂缝 (A组)	PV-2	7.59	23.78	48.90	51.64	22.88	39.28	53.46
	PV-3	7.45	23.70	45.33	51.64	22.88	38.86	42.43
	PV-5	7.33	22.59	43.15	50.24	22.86	35.96	41.70
	PV-9	6.71	20.10	36.33	42.31	22.84	33.14	37.99
(7)无缝正交各向异性体	PVA-3	7.48	23.64	45.62		22.87	45.15	
	PVA-5	7.38	22.88	44.95		22.85	42.61	
	PVA-9	6.67	19.98	36.46		22.80	32.87	

Key: (1) Cracking situation; (2) Model ID; (3) Anti-symmetry vibration pattern; (4) Normal symmetry vibration pattern; (5) Crackless; (6) Vertical crack; (7) Structure without cracks having orthogonal anisotropic properties

IV. Effects of the Cracks on the Dynamic Elastic Modulus of the Material

There are some differences of the material deformation between that having cracks and that without, even under the same stress conditions. This corresponds to the case of changing the original material elastic properties. In rock mechanics, the definition of the elastic constant of a rock with cracks or fractures is the effective elastic constant, while the elastic constant of a rock without a crack is called the fundamental elastic constant, Ref [1].

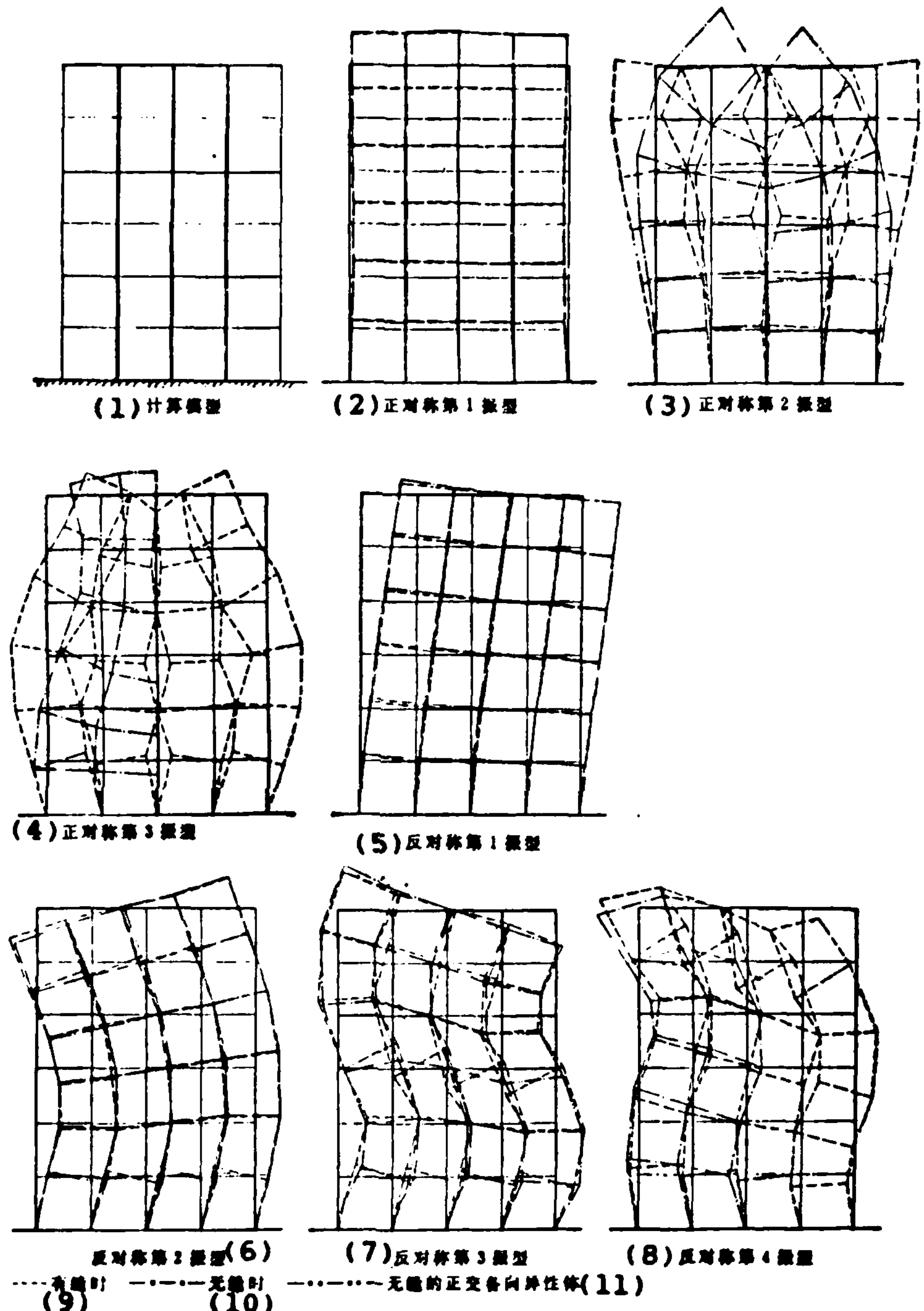

Fig. 2 Comparison of the vibration patterns of the structure with nine vertical cracks and without any cracks.

Key: (1) Calculation model; (2) First mode of normal symmetry; (3) Second mode of normal symmetry; (4) Third mode of normal symmetry; (5) First mode of anti-symmetry; (6) Second mode of anti-symmetry; (7) Third mode of anti-symmetry; (8) Fourth mode of anti-symmetry; (9) With crack; (10) without cracks; (11) Structure without cracks which has orthogonal anisotropic properties.

The dynamic elastic modulus of the material can be determined by vibrating a prismy pole longitudinally. The displacement pattern of this particular kind of vibration propagates longitudinally while it expands and contracts. This solely unique deformation excludes the complexities which could be introduced by the compounded stress and shape of a structure, and it is extremely helpful for studying the effects of cracks. The one dimensional wave equation of a prismy pole is, Ref [2],

$$\frac{\partial^2 u}{\partial x^2}=\frac{1}{a^2}\,\frac{\partial^2 u}{\partial t^2}, \tag{2}$$

where u is the longitudinal displacement of a point on the cross-section plane at x; a the is wave velocity written as

$$a=\sqrt{E/\rho}, \tag{3}$$

where E is the modulus of elasticity of the prismy pole, ρ is the material mass density. The longitudinal vibration frequency can be obtained by solving Equation (2). Its first mode frequency is

$$f_1=\frac{1}{4l}\sqrt{E/\rho}, \tag{4}$$

where l is the pole length. For the case of longitudinal vibration, substitute all parameters into Equation (4), the first vibration mode frequency of the structure without cracks is thus obtained, and it is equal to 22.88 Hz.

If the longitudinal vibration frequency of a cracked rock is given, f_e, the effective dynamic elastic modulus, E_e of the cracked material can be calculated through Equation (4). Assuming the fundamental elastic modulus and frequency of the material without cracks are E_o and f_o, respectively, from Equation (4), we have

$$E_e = (f_e/f_o)^2 E_o = \alpha E_o \tag{5}$$

where $\alpha = E_e/E_o$ is the ratio of the effective dynamic modulus of the cracked material and its fundamental dynamic modulus, and it is called a reduction coefficient.

The first mode of normal symmetry vibration of a column rock in fact is the first vibration mode when that column vibrates in the longitudinal direction (as shown in Fig. 2). From Table 1, we can see that the number of crack has litter effect on the frequency for the set A models which contain vertical cracks, and their frequencies are close to the theoretical value, 22.88 Hz that is obtained from Equation (4) for the structure without cracks. Therefore, when the deformation direction is consistent with the cracks orientation, we can conclude that the cracks have no effect on the elastic modulus at that particular direction. This means that the effective elastic modulus is equal to the fundamental elastic modulus.

For the set B models which have horizontal cracks, because the stress direction is in orthogonal to the crack direction, the

effects of cracks on the frequency are obvious, as shown in Table 2; its effective dynamic elastic modulus decreases along with the increase of the number of cracks. Fig. 3 shows the relation of the reduction coefficient α and the crack parameter c^2L as expressed as

$$E_e = \frac{E_0}{1+2(c^2L)^{0.78}}, \tag{6}$$

This relationship can be approximately applied to general cases. In the parameter c^2L, where c is 1/2 of the crack length, and $L=1/bd$ which is the number of cracks of a unit volume.

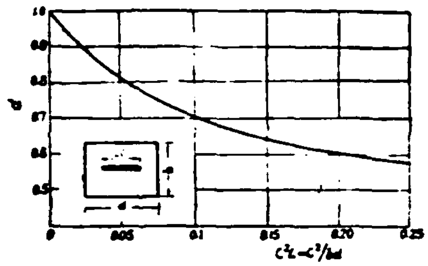

Fig. 3 Variation of the reduction coefficient α with respect to c^2L.

Table 2 Value of α for the cases of various number of the horizontal cracks.

(1)	C^2L	(2)	f_e/f_0	$\alpha=E_e/E_0$
0	0	22.91	1.0	1.0
1	0.0417	20.91	0.913	0.833
3	0.125	18.87	0.824	0.678
5	0.2083	18.14	0.792	0.627
6	0.250	17.12	0.747	0.558

Key: (1) Crack number; (2) Longitudinal vibration frequency (Hz)

V. The Approximate Dynamic Analysis Method of a Cracked Rock Structure

There are two cases where the entire rock mass can be treated as a structure without cracks which has orthogonal anisotropic properties. One is when the density of joints and cracks in the rock distributes uniformly and the joints orient solely in one direction. The other is for two sets of perpendicular joints structure; if the shear force between rocks is large and under a non-slip condition; the effects of cracks on the material elastic properties are different at both parallel and perpendicular directions. The effective dynamic elastic modulus of the rock, E_e, at the direction parallel with the crack direction (i.e. Z direction as shown in Fig. 4) is equal to its fundamental dynamic elastic modulus, E_o, while the effective dynamic elastic modulus, E_Y, at the direction perpendicular to the crack direction (Y direction) can be determined, based on the crack parameter c^2L through Equation (6). For a multiple-layer rock whose length and density of the cracks of each layer are different, each layer can be treated as a structure without cracks which has orthogonal anisotropic properties

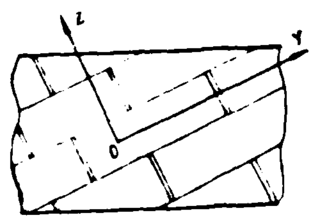

Fig. 4.

The free vibration characteristics were calculated for the model PV-3, PV-5 (a multiple-layer case) as well as PV-9 in the Fig. 1 by using the method stated above. The results were also listed in Table 1 for easy comparison (the symbol PVA represents the column model of a structure without cracks which has orthogonal anisotropic properties). Meanwhile, the right half side of the corresponding curves of model PV-9 and PVA-9 are plotted in Fig. 2 for comparison.

From the comparison in Table 1 and Fig. 2, it shows that the free vibration characteristic, including the vibration mode frequency and pattern, calculated by using a structure without cracks which has orthogonal anisotropic properties is absolutely feasible for the first two or three lower modes. The error of its vibration mode frequency does not exceed 2%, the error is also under 5% even for the third mode of the anti-symmetry case. Their vibration patterns are very close except at the crack locations. For those lowest modes, the effects of the cracks on the free vibration properties can be considered as having changed the material elastic properties. For the high vibration mode, especially the high normal symmetry mode (such as the second mode of the normal symmetry), as pointed out before, this method is no longer appropriate; therefore, the difference between two vibration patterns is large (in Fig. 2). This also explains the nonlinear property of the crack problem.

Table 3 lists the comparison of the maximum frequency response values between the model PV-5 and PVA-5 for their boundary points. Those are the displacement responses which base on the conditions of the damping ratio is 0.1 and the foundation of the structure sustains a horizontal harmonic vibration with an acceleration amplitude of 0.1g. From Table 3, the responses of both models are shown to be very close; the differences of all points are less than 5% except the bottom of the Z direction displacement which is 10%. The maximum displacement responses of both models occur at the first mode of the anti-symmetry case. This explains that the estimation of the dynamic response of a simple structure by using the orthogonal anisotropic model to substitute for a cracked structure appears to be containing a certain engineering precision, because the dynamic response of a structure is mainly determined by the first few lowest vibration mode although this model is not applicable to high modes.

Table 3 Comparison of the frequency response between model PV-5 and PVA-5.

(1) 响应	(2) 模型	(3) 高度 (米)						
		0	5	10	15	20	25	30
(4) Y 向 (10-[illegible] 米)	PV-5	0	0.36	0.88	1.43	2.04	2.66	3.22
	PVA-5	0	0.37	0.85	1.41	2.00	2.60	3.17
(5) Z 向 (10-[illegible] 米)	PV-5	0	0.47	0.71	0.90	1.01	1.05	1.03
	PVA-5	0	0.42	0.71	0.89	1.00	1.04	1.05

Key: (1) Response; (2) Model; (3) Height (meter); (4) Y direction ; (5) Z direction.

VI. Compare With the Model Test Results

The experiment model is a plane slice hill as shown in Fig. 5. The material of the model is made of plaster and barite powder. Its volume density is 2.4 ton/m^3, the dynamic elastic modulus $E_o = 5.73 \times 10^4$ ton/m^2. The model has five layers and is staggered of a total of 40 pieces of 5x5x5cm plaster bricks. In order to keep from collision, a 1.5mm gap is left between two vertical bricks, while all horizontal gaps are glued. In order to make a comparison, a single piece but shape similar to the hill model is also made. The vibration test is conducted on an electro-magnetic hydraulic supported vibration platform. A piezoelectric accelerometer is used to measure the first vibration mode. The readout is 295 Hz for the single piece hill model, and 266 Hz for the cracked model.

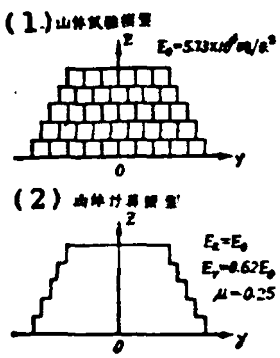

Fig. 5
Key: (1) Hill test model; (2) Hill calculation model

The dynamic analysis for both models are also carried out by the finite element method. A structure without cracks which has

orthogonal anisotropic properties is used to substitute for the first model which contains the vertical cracks. Its Y direction dynamic elastic modulus is E_y. The crack parameter c^2L of each layer is calculated through Equation (6) by choosing $E_z = E_o$. Results show that the first mode frequency of the single unit model is 297.1 Hz, while it is 266.1 Hz for the orthogonal anisotropic model. Both calculation results and the test results are consistent. This states that the finite element model used to conduct the crack dynamic analysis is correct, and the idea of analyzing the lower vibration mode by adopting the orthogonal anisotropic model is feasible.

VII. Effects of Cracks on the Structure Damping

From the relative motion of the mass points located at both sides of a crack (as shown in Fig. 2), the phenomenon of energy dissipation at the crack location while the structure in vibrating and its effect on the structure damping can be understood. Its motions can be roughly categorized into the following situations:

(1) Friction Motion It occurs mostly in the anti-symmetry vibration pattern especially at the crack which is located on the axis of symmetry. Furthermore, the relative motion of the friction increases as the vibration mode increases.

(2) Collision-Squeezing Motion It occurs mostly in the normal symmetry vibration pattern especially at the crack which is

located on the axis of symmetry. Similarly, the higher the vibration mode, the higher the vibration amplitude.

(3) Collision-Squeezing-Friction While Squeezing It occurs mostly at the crack which is not located at the axis of symmetry. During vibration, since friction occurs while squeezing, more energy dissipates than in simple collision.

Because the cracked structure consumes vibration energy through the above motions, the structure damping is therefore increased. This phenomenon is also demonstrated in model testing. The damping ratios of the first mode for the three cases of the model shown in Fig. 5 are measured and listed in Table 4. These three cases are: the single unit model, the model with vertical gaps, and the model with the vertical gaps being closed but not glued. Table 4 shows that the damping ratio of the crackless model is the smallest one; it is higher for the model with cracks, and it is the highest for the gaps closed model because collision and squeezing, as well as friction, occur in this case. Compared with the case of a structure without cracks, the damping ratio of the gaps closed model is increased by 0.085 and is around three times that of the case without cracks.

The amount of energy dissipated during collision depends on the kinetic energy of the point mass. In other words, it depends on the square of vibration velocity or vibration frequency of the point mass. The amount of energy consumed during friction depends

on the squeezing force between the gaps and the relative displacement of the point mass. Therefore, the higher the vibration mode, the higher the vibration kinetic energy consumed owing to the cracks, thus the higher the structure damping. This fact has been proved by the experiment in Ref [3].

Table 4 Damping ratio of the plaster model under different crack situations

(1) [illegible]	(2) [illegible]	(3) [illegible]	(4) [illegible]
(5) [illegible]	0.036	0.056	0.121

Key: (1) Model; (2) Crackless; (3) Gap existing in the vertical cracks; (4) Gaps closed; (5) Damping ratio.

VIII. Closure

In summary, regardless of a rock structure or a concrete structure, effects of the cracks on its dynamic properties contain three aspects: (1) the crack changes the mechanical properties of the structure material, such as elastic modulus, etc.; (2) the crack changes the damping properties of a structure and material; (3) the crack appearance changes the structure dimension, thus changes its vibration properties. The effects of cracks on the above three aspects depend not only on the crack number, length and orientation, but mainly on the vibration pattern of the structure. For the first few vibration modes, because its vibration patterns are simpler, the effect of the crack is small, and effect of the damping is also small. Its effect on the dynamic properties can be considered as the consequence of

changing its material elastic properties. Thus, an estimation of the dynamic responses of a simple cracked structure by using a structure without cracks which has orthogonal anisotropic properties is satisfied in the engineering application.

From the above analyses, for a structure like a concrete dam, the period of each mode and the damping will be increased whenever a crack appears. From the dynamic mechanics and the characteristic of the response curve, we know that the increased period will stagger the peak amplitude period which occurred while the dam is cracking. Moreover, the increase of the structure damping can decrease the response value remarkably (according to statistics, the response value can be decreased 17% while increasing damping from 0.05 to 0.1, Ref [4]). Therefore, the earthquake load will be dramatically decreased along with the crack extension of the dam and the increase of crack number, thus suppressing the structure from continuing damage.

Therefore, it is extremely necessary to explore the study of the possibility of crack occurrence under a strong vibration, and of the dynamic properties of the dam after cracks have occurred, as well as conducting the anti-seismic study further by adopting artificial crack measures.

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A Preliminary Study on the Effects of the Joints and Cracks to the Dynamic Properties of the Rock Mass and its Structure

Wang Qizheng
(Tsinghua University)

Abstract

The dynamic analyses of two groups of column rock structure including eight cases of joints are carried out by finite element method. The effects of joints on the dynamic elastic modulus of the material and on the natural dynamic behavior of the column structure are obtained. The results show that the dynamic response for a simple structure with joints can be estimated using a dynamic analysis of the structure without joint which has orthogonal anisotropic property. This conclusion is demonstrated by the results of the dynamic model test for a plane slice of a hill with joints.

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